Title
Health Impacts of Climate Change as Contained in Economic Models Estimating the Social Cost of Carbon Dioxide

Journal
GeoHealth, 5(8)

ISSN
2471-1403

Authors
Cromar, Kevin
Howard, Peter
Vásquez, Váleri N
et al.

Publication Date
2021-08-01

DOI
10.1029/2021gh000405

Peer reviewed

GeoHealth

RESEARCH ARTICLE
10.1029/2021GH000405

Key Points:
- This study assesses the incorporation of health impacts in economic models of climate change
- Improving the health functions in integrated assessment models will lead to a more accurate estimation of the social cost of carbon
- Socioeconomic factors modify the interaction between climate and health and should be considered in updates of integrated assessment models

Correspondence to:
K. Cromar,
kevin.cromar@nyu.edu

Citation:
Cromar, K., Howard, P., Vásquez, V. N., & Anthoff, D. (2021). Health impacts of climate change as contained in economic models estimating the social cost of carbon dioxide. *GeoHealth*, *5*, e2021GH000405. https://doi.org/10.1029/2021GH000405

Received 12 FEB 2021
Accepted 27 MAY 2021

Author Contributions:
Conceptualization: Kevin Cromar, Peter Howard
Formal analysis: Peter Howard, David Anthoff
Investigation: Kevin Cromar
Methodology: Peter Howard, David Anthoff
Software: Peter Howard, David Anthoff
Supervision: Kevin Cromar
Visualization: Kevin Cromar
Writing – original draft: Kevin Cromar
Writing – review & editing: Kevin Cromar, Peter Howard, Váleri N. Vásquez

Health Impacts of Climate Change as Contained in Economic Models Estimating the Social Cost of Carbon Dioxide

Kevin Cromar[1,2], Peter Howard[3], Váleri N. Vásquez[4,5,6], and David Anthoff[4,5]

[1]Marron Institute of Urban Management, New York University, New York, NY, USA, [2]Departments of Environmental Medicine and Population Health, NYU School of Medicine, New York, NY, USA, [3]Institute for Policy Integrity, New York University School of Law, New York, NY, USA, [4]Energy and Resources Group, University of California at Berkeley, Berkeley, CA, USA, [5]Berkeley Institute for Data Science, University of California at Berkeley, Berkeley, CA, USA, [6]School of Public Health, University of California at Berkeley, Berkeley, CA, USA

Abstract The health impacts of climate change are substantial and represent a primary motivating factor to mitigate climate change. However, the health impacts in economic models that estimate the social cost of carbon dioxide (SC-CO_2) have generally been made in isolation from health experts and have never been rigorously evaluated. Version 3.10 of the Framework for Uncertainty, Negotiation and Distribution (FUND) model was used to estimate the health-based portion of current SC-CO_2 estimates across low-, middle-, and high-income regions. In addition to the base model, three additional experiments assessed the sensitivity of these estimates to changes in the socio-economic assumptions in the model. Economic impacts from adverse health outcomes represent ∼8.7% of current SC-CO_2 estimates. The majority of these health impacts (74%) were attributable to diarrhea mortality (from both low- and high-income regions) followed by diarrhea morbidity (12%) and malaria mortality (11%); no other health impact makes a meaningful contribution to SC-CO_2 estimates in current economic models. The results of the socio-economic experiments show that the health-based portion of SC-CO_2 estimates are highly sensitive to assumptions regarding income elasticity of health effects, income growth, and use of equity weights. Improving the health-based portion of SC-CO_2 estimates could have substantial impacts on magnitude of the SC-CO_2. Incorporating additional health impacts not previously included in estimates of SC-CO_2 will be a critical component of model updates. This effort will be most successful through coordination between economists and health researchers and should focus on updating the form and function of concentration-response functions.

Plain Language Summary The health impacts of climate change are an important factor in cost-benefit analyses that inform policy decisions. This study shows that the values used in the currently best available economic models of climate change are not representative of the scientific understanding of the health impacts of climate change. These health functions need to be updated in order to fully account for the benefits of reducing greenhouse gas emissions. This finding supports the recent call by the US government to take concrete steps to improve how agencies consider the impacts of climate change in considering potential policy decisions.

1. Introduction

The global health impacts of climate change are substantial. An assessment released by the World Health Organization in 2018, based on a subset of relevant health outcomes, estimated that 250,000 excess deaths per year could occur between 2030 and 2050 (WHO, 2018). Based on these and other similar findings, the Director-General of the World Health Organization stated in 2016 that climate change is the defining public health issue of the 21st century. Similarly, the central finding of the 2018 Lancet Commission on Health and Climate Change shows that academics also have placed public health at the front of the climate discussion by concluding that tackling climate change could be the greatest global health opportunity of the 21st century (Watts et al., 2018). However, despite the overwhelming focus among both researchers and policymakers on the potential health impacts of climate change, there has been little academic work investigating how these benefits are actually included in the economic models, which often inform climate policy decisions.

Table 1
Health Endpoints Included in Integrated Assessment Model (IAM) Estimates of $SC\text{-}CO_2$

Explicit health effects modeling	DICE-2007[a]	DICE-2013[b]	FUND[c]	PAGE[d]	ICES 2014[e]	ENVISAGE[f]
Diarrheal Diseases			✓		✓	✓
Dengue Fever	✓		✓		✓	✓
Malaria	✓		✓		✓	✓
Schistosomiasis	✓		✓		✓	✓
Other tropical diseases	✓					
Air pollution health effects	✓					
Cardiovascular disorders			✓		✓	✓
Respiratory disorders			✓		✓	✓
Hurricane/storm damages (health)			✓			
Implicit Health Effects Modeling	DICE-2007	DICE-2013	FUND	PAGE	ICES 2014	ENVISAGE
Metaanalysis		✓				
Author discretion				✓		
Economic Effects Modeled	DICE-2007	DICE-2013	FUND	PAGE	ICES 2014	ENVISAGE
Willingness to pay	✓	✓	✓	✓		
Labor productivity					✓	✓
Demand shock					✓	✓

Note. The three models traditionally used by the US in policy decisions model the consumption impacts of climate change (i.e., DICE, FUND, and PAGE). Of these, only the FUND model explicitly models health endpoints in making $SC\text{-}CO_2$ estimates, which is why it was used as the basis for this study. FUND, Framework for Uncertainty, Negotiation and Distribution.
[a]Nordhaus (2008). [b]Nordhaus and Sztorc (2013); Nordhaus (2014). [c]Waldhoff et al. (2011). [d]Hope (2013); Moore et al. (2018). [e]Boselloand and Parrado (2014). [f]Roson and van der Mensbrugghe (2012).

Economic models of climate change weigh the climate-related benefits of greenhouse gas mitigation, including health benefits, against the costs of policy action along specific future scenarios. This is done by applying social cost of carbon dioxide ($SC\text{-}CO_2$) estimates within a cost-benefit framework to estimate the net economic value of policy actions taken to reduce carbon emissions. The $SC\text{-}CO_2$ represents the estimated economic impacts of a unit increase of carbon dioxide (CO_2) emissions: thus, it constitutes a marginal cost estimate of CO_2 emissions. $SC\text{-}CO_2$ is typically expressed in US dollars and includes impacts caused by sea-level rise, on public health, on agriculture productivity, changes in energy consumption, and other relevant areas of impact (Howard, 2014; NASEM, 2017).

Integrated assessment models (IAMs) that estimate the $SC\text{-}CO_2$ or predict climate damages more generally (e.g., DICE/RICE [Nordhaus, 2018], Framework for Uncertainty, Negotiation and Distribution [FUND] [Waldhoff et al., 2011], PAGE [Hope, 2013; Moore et al., 2018], ENVISAGE [Roson & van der Mensbrugghe, 2012], and ICES [Bosello, 2014; Bosello et al., 2012]) include some contribution of health impacts in estimating economic damages of climate change. However, they differ in which health impacts they capture as well as how they model those health impacts; key differences are summarized in Table 1. Three of the IAMs primarily used in $SC\text{-}CO_2$ analysis (i.e., DICE, PAGE, and FUND) use the same conceptual framework to value health impacts caused by climate change: first, a change in climate is assumed to change the risk of prematurely dying (and morbidity risk). Second, those risk changes are valued using estimates of the willingness to pay for health risk reductions (e.g., the value of a statistical life, or VSL) (Calel & Stainforth, 2017). Other IAMs, like ICES and ENVISAGE, use an alternative method for estimating marginal health costs of climate change that does not include the value of a statistical life (VSL): These models instead assess changes in labor productivity and demand for healthcare.

The $SC\text{-}CO_2$ is not an end-all measure in informing how much action should be taken to mitigate climate change, but estimates of the economic impacts of climate policy are widely seen as an important input for reasoned and informed policy decisions (Nordhaus, 2008). Given the intense focus on the public health impacts of climate change, as well as the importance of economic analysis in reasoned policy decisions, it is essential that the health impacts of climate change as included in SC-CO_2 estimates are clearly understood and explained to the broad range of audiences whose work informs and is informed by climate research. Furthermore, it is hoped that engagement with a broader range of subject-matter experts will ultimately result in an improvement in SC-CO_2 estimates. This paper is a first step toward broader engagement by making available detailed information on how health impacts are considered in economic models of climate change.

The specific goals of this paper are to evaluate the health-based portion of existing SC-CO_2 estimates, to describe the results of experiments that test the sensitivity of these estimates to changes in the socioeconomic assumptions that are included in these models, and to identify ways in which the health-based portion of SC-CO_2 estimates can potentially be improved. The Climate FUND model is used as the basis for this analysis since it is the only cost-benefit IAM that has an explicit representation of health impacts. This structural representation of specific health endpoints, including cardiovascular and respiratory diseases, malaria, and schistosomiasis, allows scientists and economists to disaggregate the nonlinear and potentially disparate effects of climate change on public health. The decision to use the FUND model for this work is not to claim that it provides the most accurate estimate of SC-CO_2; rather, it is currently the only available model that is structured in a way that allows for this kind of analysis.

2. Materials and Methods

All results in this study were computed using version 3.12.1 of the FUND model (Anthoff & Tol, 2018). The FUND model is open source and available at www.fund-model.org/. The model was used in its deterministic configuration that is documented on the FUND website. Given this deterministic configuration, the assumptions and parameter specifications used for each experiment are essential context for analyzing the SC-CO_2 estimates that result: in all cases, SC-CO_2 estimates carry a high degree of uncertainty, and are dependent on these details. Other interested end-users can access the open source FUND model to replicate the experiments in this analysis or to conduct their own experiments.

To calculate SC-CO_2 for a ton of additional CO_2 emission in a given year, the difference in the present value of total climate costs is determined by running FUND with the base parameter values, and then again with an additional megaton of CO_2 emissions added in the starting year, which is then standardized to 1 ton by dividing by 1 million. The estimates aggregate the damages caused by this marginal emission over the time span 2010–2250. The same calculation method is used to determine the proportion of the SC-CO_2 attributable to each health endpoint by using the parametric specification of the mortality and morbidity costs of each health endpoint. These results were then successfully double checked by comparing to values to those obtained by recalculating the SC-CO_2 after rerunning FUND with mortalities and morbidities for each endpoint zeroed out.

The procedure was then repeated at regional scale for each of the 16 regions in FUND to calculate regional SC-CO_2 estimates (which inherently ignores potential spillover effects). These regional results were aggregated into one of three economic regions based on GDP per capita estimated over the study period: low income regions (South Asia, Sub-Saharan Africa, former Soviet Union, and North Africa); middle income regions (South America, Central America, Middle East, Central and Eastern Europe, Southeast Asia, Greater China, and Small Islands States); and high income regions (United States, Canada, Western Europe, Japan and South Korea, and Australia and New Zealand).

Three experiments on how income affects the SC-CO_2 via health impacts were conducted by changing various parameter values in the underlying health impact equations. The purpose of these experiments in the context of this analysis is to determine the sensitivity of health impacts when modifying the socio-economic assumptions on the FUND model. Though the exact equation specifying the relationship between climate change and each health point is unique, generally the monetized climate-induced mortality due to health endpoint v in period t and region r is:

$$D_{t,r}^{v} = B_{t,r} * \mathrm{VSL}_{t,r} * f_{r}^{v}\left(T_{t,r}, P_{t,r}\right)\left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\omega^{v}}$$

where B is the discount factor, a rate-based variable used to estimate the current value of future costs and benefits; VSL is the value of statistical life, a measure used to estimate willingness to pay for mortality risk reductions; $f_r^v\left(T_t, P_{t,r}\right)$ is a region r specific mortality function for health endpoint v, and is a function of temperature increase $T_{t,r}$ (for some health endpoints v this is regional temperature, for some it is global temperature) and population size $P_{t,r}$; y is GDP per capita; and ω is the elasticity of the health endpoint to per capita income, that is, an income elasticity, reflecting the responsiveness of health risk to changes in income. More specifically:

$$B_{t,r} = \left(\frac{y_{2010,r}}{y_{t,r}}\right)^{\eta} \left(1+\rho\right)^{2010-t}$$

and

$$\mathrm{VSL}_{t,r} = \delta\left(\frac{y_{t,r}}{y_0}\right)^{\lambda}$$

where η (equal to 1) is the elasticity of the marginal utility of consumption, which measures how utility (i.e., benefit) changes with consumption; ρ (equal to 1%) is the pure rate of time preference, otherwise known as the rate at which the value of future utility declines; λ (equal to 1) is the elasticity, or measurement of percent change, of the VSL in response to a change in income; and δ (equal to 4,992,523) is the VSL, when GDP per capita equals the constant y_0 (equal to 24,963). In the first experiment, the income elasticity of each health endpoint, with the exception of cardiovascular and respiratory disease for which no elasticity is specified in the model, was set equal to zero (i.e., $\omega = 0$). This is designed to examine the effect of the assumption that climate impacts, reflected as mortality and morbidity, are completely independent of changes in future per capita income levels. In such a scenario, vulnerability does not change with changing income. In a second experiment, it was assumed that developing regions will be stuck in a poverty trap from 2010 onwards through the study period, such that GDP per capita remains constant at its 2010 level (i.e., $\mathrm{ypc} = \mathrm{ypc}_{2010,r}\ \forall t > 2010\ \&\ \forall r \in \text{Developing Regions}$). It is anticipated that these experiments should affect both the dollar magnitude of health impacts as well as modifying the fraction of the SC-CO_2 attributable to health impacts because each experiment affects both of the runs necessary to calculate the SC-CO_2 (the base run and plus one megaton scenarios), while also affecting nonhealth endpoints.

A final experiment is conducted in FUND using equity weights (Anthoff & Tol, 2009, 2013). Because the marginal utility of consumption (the amount of utility that society gains from an additional dollar of consumption) differs between regions and time periods, equity weights give more weight to income in poor regions than rich regions by normalizing to a common unit of measurement: the 2010 dollar value in a reference region. To include equity weights, the discount factor above is replaced with:

$$B_{t,r} = \left(\frac{y_{2010,\mathrm{ref}}}{y_{t,r}}\right)^{\eta} \left(1+\rho\right)^{2010-t}$$

where $y_{2010,\mathrm{ref}}$ is the 2010 GDP per capita in the reference region. While the reference region can be any region, this analysis used Pearce equity weights based on a global value such that $y_{2010,\mathrm{ref}}$ is the 2010 global average GDP per capita (Anthoff & Tol, 2013; Fankhauser et al., 1997). The choice of reference region affects the magnitudes of the SC-CO_2, but does not affect the percentage the SC-CO_2 corresponding to health impacts.

3. Results

3.1. Health-Based Portion of SC-CO_2 Estimates

Health damages comprise a relatively small, but important, portion of the SC-CO_2 as currently estimated in FUND. Table 2 shows that the estimated present value of economic damages of a metric ton of CO_2 emitted in 2015 using a discount rate to be \$20.00, where the discount rate is calculated using the standard Ramsey approach recommended by the National Academies of Science, which accounts for the pure rate of time preference, the growth rate of per capita consumption, and a measure of relative risk aversion (NASEM, 2017). The health-based portion of this \$20.00 SC-CO_2 estimate is \$1.74 (8.7%). For context, this is greater

Table 2
$SC\text{-}CO_2$ by Category and Economic Region

Category	Total $SC\text{-}CO_2$ (2015$)	High income region	Medium income region	Low income region
Energy consumption	19.39	10.29	6.25	2.85
Agriculture	−6.14	−3.00	−3.54	0.41
Water resources	2.90	0.82	0.25	1.83
Health	1.74	0.63	0.14	0.97
Ecosystems	1.54	1.56	0.00	−0.02
Forestry	−0.13	−0.10	−0.02	0.00
Sea level rise	0.47	0.25	0.15	0.07
Storms (nonhealth)	0.21	0.17	0.03	0.01
Total	20.00	10.61	3.26	6.13
Health percent of $SC\text{-}CO_2$	8.7%	5.9%	4.4%	15.9%

Note. $SC\text{-}CO_2$ values are shown in 2015 USD for each category and economic region. The percent of $SC\text{-}CO_2$ attributable to health impacts is shown as a percentage for total $SC\text{-}CO_2$ and by economic region. The absolute dollar amount assigned to health impacts and the percentage of total $SC\text{-}CO_2$ attributable to health outcomes is highest in low-income regions.

than the estimated economic impacts from sea-level rise, water resources availability, nonhealth impacts of storms, and loss of biodiversity/ecosystems but is much less than the estimated economic impacts from energy demand in high-, middle-, and low-income regions. The magnitude of the health-portion of $SC\text{-}CO_2$ estimates is also much lower than for agricultural impacts albeit in the opposite direction. Figure 1 shows a breakdown of $SC\text{-}CO_2$ by category and by income regions and also shows a map of the countries included in each economic region.

Looking more closely at the specific health endpoints, climate-related communicable disease risk is by far the most important contributor to the health-based portion of $SC\text{-}CO_2$ estimates as currently estimated in the FUND model as shown in Figure 2. More specifically, estimated health damages are vastly attributable to increased diarrhea mortality (74.1%), followed distantly by diarrhea morbidity (12.3%) and malaria mortality (10.9%). The only other endpoint with greater than 0.3% contribution to the health-based portion of $SC\text{-}CO_2$ estimates is mortality from hurricanes and extra-tropical storms (2.6%).

Health-based economic damages varied across the 16 separate regions included in the FUND model, which were aggregated into one of three groups (high-, middle, and low-income) based on GDP per capita values over the entire study period, see Figure 1 for additional details. Economic damages attributable to health are estimated to occur in both high- and low-income regions. Mortality and morbidity estimates in the high-income regions are generally low, but even small increases in these risks are valued at high dollar prices because VSL estimates are much larger in high-income regions. In low-income regions, the opposite holds true: While VSL estimates are relatively small, the estimated number of deaths and morbidities are very high.

This discrepancy arises because income elasticity, or the responsiveness of a given demand to changes in income, is a key element for estimating the VSL. The elasticity shifts the proportion of wealth being assigned to avert potential mortality, and as such is capped at the total wealth level of the individual, or in this case, regional population, being examined. The difference in per capita GDP among different nations therefore naturally gives rise to a gap between what wealthy or poor nations are able, and therefore to some measure willing, to pay for the luxury of reducing possible death versus basic daily needs. This translates to lower VSLs for regions with lower income levels, an efficiency measure that seeks to assign preference for risk reduction according to the precept of "willingness to pay." Selecting a baseline VSL consisting of per capita GDP that is applicable to all nations, and then experimentally adjusting the income elasticity of health effects in accordance with presumed responsiveness to income changes, is one approach for adjusting VSL estimates derived for high income countries such that they can be plausibly applied to low income countries (Bosworth et al., 2017; Chang et al., 2017; Viscusi & Masterman, 2017).

As shown in Figure 2, diarrhea mortality is not only estimated to be an important contributor toward the health-based portion of $SC\text{-}CO_2$ estimates due to impacts in the poorest developing regions of the world (45% of health-based portion of $SC\text{-}CO_2$ due to diarrhea mortality in South Asia, Sub-Saharan Africa, former Soviet Union, and North Africa) but also due to estimated climate-related diarrhea impacts in regions with the most advanced economies (35% of health-based portion of $SC\text{-}CO_2$ due to diarrhea mortality in United States, Canada, Western Europe, Japan/South Korea, and Australia/New Zealand). Diarrhea mortality/morbidity in middle income regions (South America, Central America, Middle East, Central and Eastern Europe, Southeast Asia, China, and Small Islands States) comprises 7.2% of the health-based $SC\text{-}CO_2$ estimates.

Climate-related malaria mortality is estimated to only be a meaningful contributor to $SC\text{-}CO_2$ in low-income regions of the world. 11% of the health-based portion of $SC\text{-}CO_2$ estimates due to malaria mortality occur in low-income regions with very little impact estimated in middle- and high-income regions. The

10.1029/2021GH000405

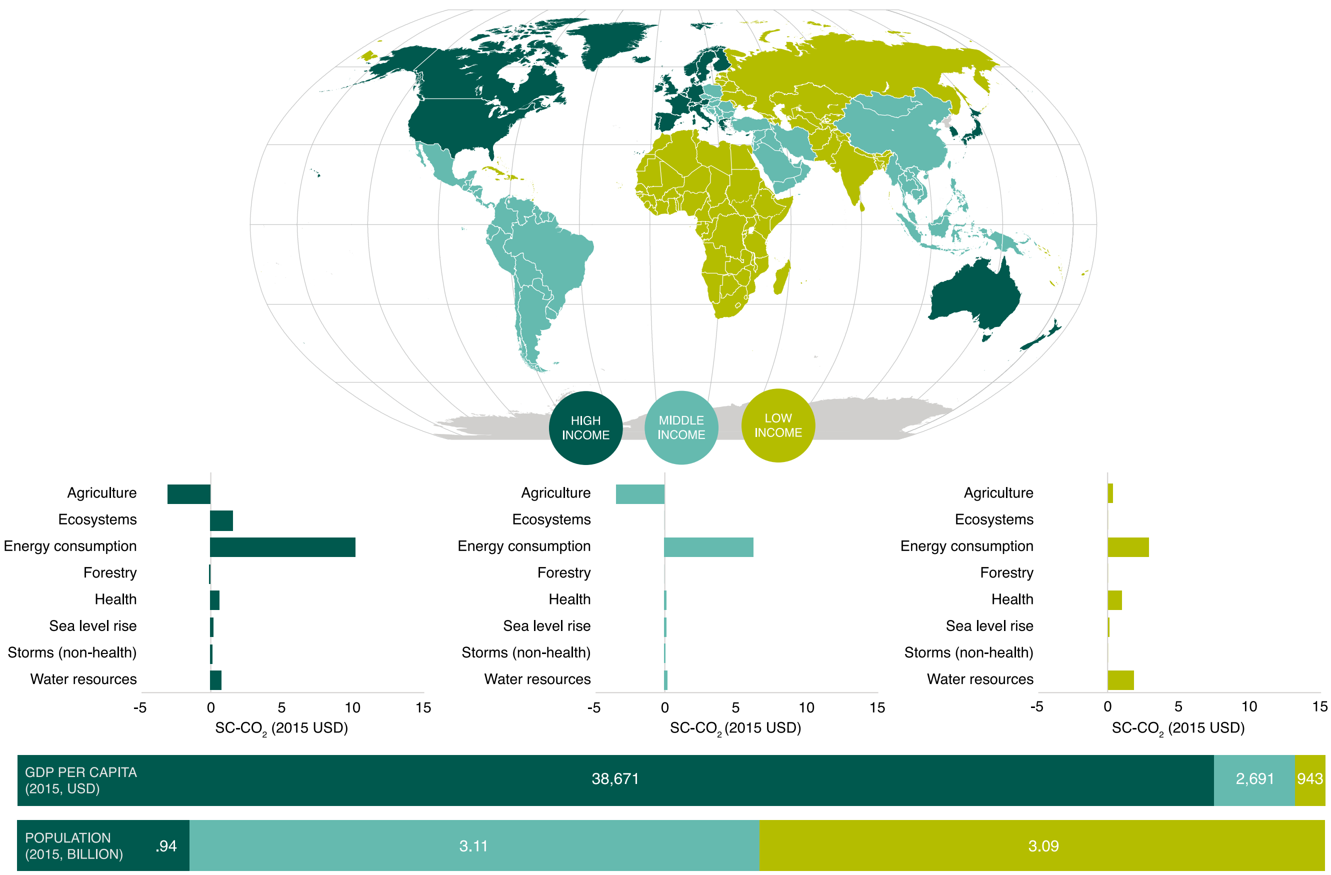

Figure 1. $SC\text{-}CO_2$ estimates shown by category and income region. The 16 regions modeled in Framework for Uncertainty, Negotiation and Distribution (FUND) were aggregated into three regions based on gross deomestic product (GDP) per capita. $SC\text{-}CO_2$ estimates by category are shown for each of these three income regions shown on the global map. The combined GDP per capita and population size are shown for each economic region based on 2015 values.

impacts of hurricanes and tropical storms are divided fair evenly between high-, middle-, and low-income regions (1.0%, 0.8%, and 0.8% of the health-based portion of $SC\text{-}CO_2$ estimates, respectively). However, it is important to note that these are the estimates of the non-market health damages of storms; other impacts of such storms are also estimated by FUND but not included in the numbers presented here.

3.2. Sensitivity of Climate-Health Estimates Based on Socioeconomic Assumptions

In addition to the base model, which was used to elucidate the contribution of health impacts in $SC\text{-}CO_2$ estimates, three additional experiments were completed to assess whether climate impacts on health are sensitive to changes in income over time. These experiments are important in determining whether health damages as estimated in FUND and other economic models are not only impacted by the choice of health endpoints and their associated damage functions, but also to the socio-economic assumptions included in the models. The two alternative economic scenarios considered are: setting the income elasticity of health effects to zero for only the health sector; and modeling a "poverty trap" scenario where per capita income does not increase in developing regions. It is important to note that these scenarios are not meant to model the expected changes in income over time, but rather to demonstrate how our assumptions regarding income growth over time and by region may impact the direction and magnitude of the health-based portion of $SC\text{-}CO_2$ estimates. It is also important to note that these experiments can provide valuable information despite any limitations due to the need for updated damage functions or exclusion of other important health impacts from the model.

Figure 3 shows $SC\text{-}CO_2$ estimates, the health-based portion of $SC\text{-}CO_2$, by region for our base model and these two experiments. In these experiments, both the absolute magnitude and the percentage of total

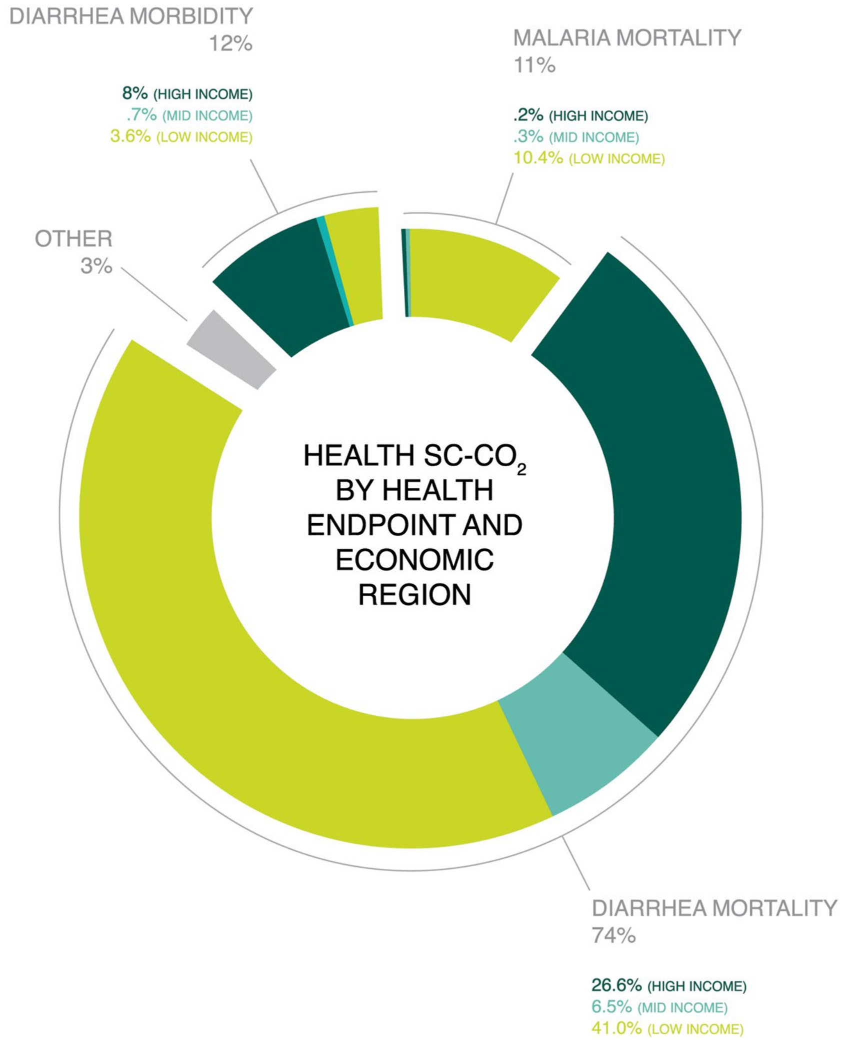

Figure 2. Breakdown of Health SC-CO_2 by health endpoint and economic region. Percentages of the health portion of SC-CO_2 is shown by health endpoint and further shown by economic region. Diarrhea mortality in low-income regions (41.0% of health SC-CO_2), followed by diarrhea mortality in high-income regions (26.6% of health SC-CO_2), are the two largest contributors to the health-based portion of SC-CO_2 in Framework for Uncertainty, Negotiation and Distribution (FUND). All other health endpoints (including diarrhea mortality in middle income regions, diarrhea morbidity in all regions, and all other health endpoints in all regions) combined comprise 32.4% of health SC-CO_2.

SC-CO_2 were increased for the health-based portion of SC-CO_2. This was particularly true for the low-income regions, which had the greatest increases in health-based SC-CO_2.

The income elasticity of health effects measures how the vulnerability of society to climate-related health risk changes as per capita income changes. In other words, this parameter captures the increasing adaptation capabilities that occur with higher levels of income. When the income elasticity for the health sector is set equal to zero, climate impacts in terms of number of deaths or years of morbidity is entirely independent of changes in per capita income levels that are assumed in future years. The result of this experiment is that the total number of climate-related deaths greatly increases. The value of each life lost, as expressed by VSL, remains the same as in the base run (i.e., the VSL is still changing with per capita income levels) and all nonhealth climate impacts remain as they were in the base run. As a result of each of these changes, the health-based portion of SC-CO_2 increases dramatically across all economic regions from $1.75 (8.7% of SC-$CO_2$) to $12.34 (40.5% of SC-$CO_2$), when income elasticity in the health sector is set to zero as compared to our base model.

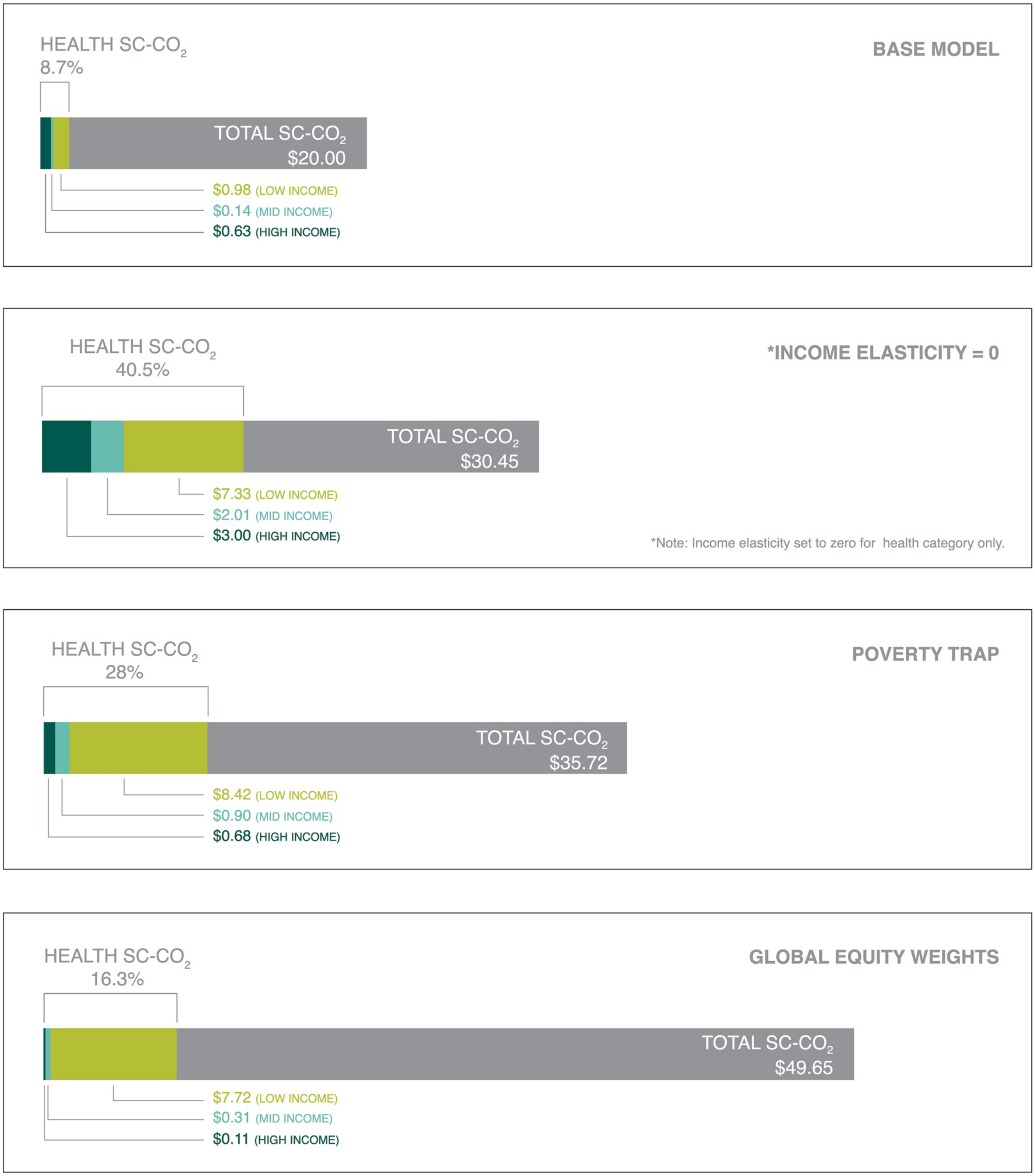

Figure 3. SC-CO_2 estimates and health-based portion of SC-CO_2 by region following experiments with socio-economic assumptions and use of global equity weights. The total SC-CO_2 and the health-based portion of SC-CO_2 by income region is shown for the base mode, the two experiments testing socioeconomic assumptions, and the use of global equity weights. The two experiments modifying the socioeconomic assumptions of the base model do not reflect what is expected to occur but rather demonstrate the sensitivity of the health-based portion of SC-CO_2 modification of these assumptions.

The poverty trap scenario resulted in dramatic increases in the total number of climate-related deaths but also a decrease in VSL over the time period considered in this study, but only in developing regions. All impacts in developed regions remain the same as compared to our base model because it is assumed that there are no interactions (e.g., trade) across regions. The counteracting directions of these changes resulted in an overall increase in the health-based SC-CO_2 estimate despite having a much lower VSL in the low-income region.

While these experiments are not reflective of best estimates regarding what is likely to occur, they demonstrate that current estimates of climate change impacts on health are highly sensitive to assumptions regarding changes in income over time. Most significantly, if currently poor regions do not have dramatic improvements in economic growth as currently assumed in climate economic models, the relative economic damages of climate change on health substantially increases despite the opposing directions of increased health impacts (modeled in isolation in the income elasticity experiment) and decreased VSL.

3.3. Equity Weighting and Differences in Mortality Risk Valuation Between Global Regions

A particularly difficult challenge in quantifying the economic valuations of climate-related health outcomes is deciding how to reconcile the value of health impacts simultaneously occurring in both poor and wealthy regions of the world. Over long time scales, there is seemingly a conflict between the vast majority of deaths occurring in low-income regions (in particular sub-Saharan Africa) and the total share of health impacts in the SC-CO_2 being relatively equal between poor and rich nations. The explanation for this observation is that the value of a statistical life (which is the unit value of one additional death in a region) is higher for regions with high per capita income levels. From an economic point of view, this is a well-established result: willingness-to-pay estimates like the value of a statistical life are income dependent and will generally be higher for high income individuals. Nevertheless, this result seems to contradict social norms about the treatment of poor and the less fortunate (Adler, 2016). If an individual or collective society feels uncomfortable with the above results, it may be because that they are subconsciously questioning the fairness of using income dependent willingness to pay estimates, that in essence give less weight to impacts in poor regions.

One commonly employed solution to this problem is the use of equity weights in the calculation of SC-CO_2. Equity weights, also known as distributional weights, are based on the intuition that the welfare impact of a dollar to someone who is poor is larger than to someone who is rich (i.e., marginal utility of consumption is declining) (Adler, 2016). While the base version of FUND assumes that a dollar of impact is the same regardless of where it occurs (to rich or poor), the equity weighting version of FUND gives more weight to a dollar loss in a poor region than to a dollar loss in a rich region by applying weighting factors to impacts before they are summed across regions. Thus when it comes to health, equity weights apply greater weight to health impacts in poor regions (or more specifically regions during poor time periods) potentially counteracting the effect of widely differing values of statistical life.

To determine how the health-based portion of SC-CO_2 estimates may vary when using equity weights, Pearce equity weights were utilized in an experiment and compared the results to the base model. Global weights were used in this experiment, though Anthoff and Tol (2009) note that US weights should be used when completing US-based cost-benefit analysis. Ultimately the choice of which equity weight to use is insignificant for our purposes since the choice of which equity weight to use only affects the total value of the SC-CO_2 estimates, but not the ratio of the health-based portion of SC-CO_2 to the total SC-CO_2 estimate.

Using global equity weights did not change the absolute number of health impacts as compared to the base model but the valuation of these impacts does change. In the base model, the SC-CO_2 attributable to health impacts in low-income versus high-income regions was comparable, \$0.98 and \$0.63, respectively. As shown in Figure 3, following the use of equity weights, these values changed to \$7.70 and \$0.11, respectively. In addition to dramatically shifting the value of health impacts toward poorer regions, the overall percentage of total SC-CO_2 estimates attributable to health increased from 8.7% to 16.4% with the use of global equity weights.

4. Discussion

This study provides strong evidence in support of the January 20, 2021 Executive Order by the United States that calls for an improved accounting of the benefits of reducing climate pollutants in order to "accurately determine the social benefits of reducing greenhouse gas emissions" (Executive Order 13990, 2021). The FUND model's structural representation of mortality and morbidity impacts for each health endpoint as parametric equations of temperature will be familiar to most epidemiologists and other health researchers. This makes the FUND model an ideal starting point from which these fields can critique and improve economic-climate models' representation of health impacts from climate change. Unfortunately, most other IAMS are not currently designed in a way that allows for advancements in scientific understanding of the health impacts of climate change to be readily incorporated into the models, see Table 1.

The health impacts included in the SC-CO_2 estimates described in this study are not suggesting that these are the actual climate impacts on health from climate change. Rather, the results herein demonstrate what health impacts are currently being considered in economic policy tools and explore their sensitivity to various socio-economic assumptions. The economic models used to estimate SC-CO_2, including the FUND model used in this study, have been developed largely in isolation from health experts that study climate-related health impacts, and the health impact formulations are ripe for updates based on the latest and best understanding of climate-related impacts either for communicable or noncommunicable disease risks (USGCRP, 2016). It is clear from these findings that there is a pressing need to update how health impacts are incorporated into economic models of climate change.

Despite the FUND model's relative strength in modeling disease-specific health impacts from unit changes in CO_2, there is a pressing need for improvements to the health-based portion of the model. The analysis in this study clearly demonstrates that FUND estimates diarrhea mortality to be the predominate driver of health based SC-CO_2 estimates in both low- and high-income regions, see Figure 2. However, it is noteworthy that the assessment as to how diarrhea mortality risk is expected to change as a function of temperature in the current FUND model is not based on the available epidemiology literature but rather was calculated internally using cross-sectional analysis of data provided in the 1996 Global Burden of Disease report (Murray et al., 1996). Even in high-income countries, it is expected that water-related infections are likely to increase as a result of increased water temperatures altering the timing and locations of pathogens and toxins (Trtanj et al., 2016). However, the increased exposure and risk of water-borne illnesses is unlikely to have the largest health-related economic damages from climate change in high-income countries once the FUND model is updated with the scientific communities understanding on the health impacts of climate change (Kolstad & Johansson, 2011).

Temperature related noncommunicable disease risk, such as for cardiovascular mortality due to cold as well as cardiovascular and respiratory mortality due to heat, does not meaningfully contribute to the health-based portion of SC-CO_2 estimates in the FUND model, see Table 3. Near zero net impacts from heat and cold for noncommunicable diseases is was originally explained by the negative cardiovascular and respiratory damages from heat as being offset to some extent by positive health impacts of temperature increase reducing cardiovascular mortality from cold, although the magnitude of this offset has generally been shown to be less than observed in the FUND model (Arbuthnott et al., 2016; Balbus et al., 2016; Carleton et al., 2020; Gasparrini et al., 2017; Hajat, 2017; Honda et al., 2014; Schwartz et al., 2015). The incorporation of the latest health research would be expected to have a net increase in heat and cold mortality with increasing temperatures. However, even when considering these impacts in isolation, the total magnitude of damages is very small relative to communicable disease risk. This may be partially due to the need for updated damage functions but is also attributed in part to the observation that the majority of noncommunicable damages do not occur in the near-term which further minimizes their impact as a contributor to current SC-CO_2 estimates (due to the discounting of consumption and its loss over time).In addition to updating the form and function of the concentrations-response functions that describe the relationship between temperature and existing health endpoints in the FUND model, there is also a pressing need to incorporate other known climate-related health impacts into the model. In particular the health impacts from changes in ambient air quality (due to changes in pollutant concentrations from altered atmospheric chemical processes [Fann et al., 2021]; temperature- and methane-driven influences on ozone formation [Davis et al., 2011; Van Dingenen et al., 2018]; impacts on aeroallergens and respiratory disease [Albertine et al., 2014]; changes in

Table 3
Health $SC-CO_2$ by Health Endpoint, by Economic Region

Health endpoint	Total health $SC-CO_2$ (2015$)	High income region	Medium income region	Low income region	Percent of health $SC-CO_2$
Diarrhea	$1.507	$0.604	$0.124	$0.779	86.4%
Malaria	$0.195	$0.004	$0.005	$0.187	11.2%
Storms	$0.045	$0.018	$0.013	$0.014	2.6%
Dengue fever	$0.004	$0.001	$0.001	$0.002	0.2%
Cardiovascular (heat)	$0.002	$0.001	$0.000	$0.001	0.1%
Respiratory	$0.000	$0.000	$0.000	$0.000	0.0%
Cardiovascular (cold)	−$0.002	−$0.001	$0.000	−$0.001	−0.1%
Schistosomiasis	−$0.006	−$0.001	−$0.002	−$0.004	−0.3%
Total	$1.745	$0.626	$0.142	$0.977	100%

Note. Health $SC-CO_2$ values are shown in 2015$ USD for each health category and economic region. The percentage of health-based $SC-CO_2$ is shown for each health endpoint. The health endpoints consist of valuations for both mortality and morbidity impacts.

the frequency and magnitude of wildfire-related air pollution [Barbero et al., 2015]; and changes in the frequency and magnitude of dust storms [Munson et al., 2011; Tong et al., 2017]), additional vector-borne diseases (Gage et al., 2008), food related infection (Boxall et al., 2009; Lake et al., 2009), reduced nutrient content in crops from CO_2 fertilization (Beach et al., 2019), increased exposure to ultraviolet radiation due to stratospheric ozone depletion by nitrous oxide (Portmann et al., 2012), and impacts on mental health and well being (Bei et al., 2013; Dodgen et al., 2016; Hanigan et al., 2012; Kessler et al., 2008). All are pertinent health endpoints that should be included in updated versions of the FUND model. Successfully incorporating these health endpoints will require the coordinated effort between economists and health researchers to ensure its validity and accuracy.

Recommendations on how to improve future $SC-CO_2$ estimates have been well described by the National Academies in a January 2017 report (NASEM, 2017). Here, we specify two immediate health research needs that would improve future economic models of climate change. First, understanding temperature and health relationships on a regional basis, including describing any nonlinear associations, would immediately improve these global models. Second, and perhaps more importantly, there is a need to better understand the impacts of income on climate-related health risks. The results of this study demonstrate that health-based portions of $SC-CO_2$ estimates are sensitive to socioeconomic assumptions regarding income growth over time, see Figure 3. These impacts may be equally, if not more, important to resolve than the temperature-health relationships alone in creating accurate estimates of the health-based portion of the $SC-CO_2$.

In addition these issues, this analysis shows that the use of equity weights dramatically alters the relative contribution of health versus nonhealth climate impacts and these impacts merit additional research. From a global governance perspective, use of equity weights has the potential to provide $SC-CO_2$ estimates that maximize global social welfare. It is noteworthy to mention here that, after moving in the opposite direction in their use of $SC-CO_2$ in policy decisions for several years, the new US administration has reinstated $SC-CO_2$ as a tool in their climate change assessments (IWG, 2021; US EPA, 2018). From a health perspective, the use of equity weights nearly doubles the portion of $SC-CO_2$ estimates attributable to health impacts in a way that is perhaps more in line with general sentiment regarding the motivations for addressing the adverse impacts of climate change.

$SC-CO_2$ estimates, including the health-based portion of $SC-CO_2$ estimates, are highly sensitive to a large number of assumptions: scenarios of future greenhouse gas emissions; population, and economic growth rates; and the choice of damage function and discount rate (a measurement of the consumption tradeoff over time) have all been identified as particularly important previously (Howard, 2019; IWG, 2010; NASEM, 2017). Estimates of the health damages from climate change in economic models may also be improved by incorporating the likelihood of health breakthroughs (e.g., development and dissemination of improved vaccines for infectious diseases) that would render current long-term estimates moot. Other areas of climate economic research have focused more explicitly on climate adaptation in their damage estimates which is an approach that deserves continued attention and refinement (Carleton et al., 2018).

5. Conclusions

There is a clear need for improvement in incorporating accurate representations of the health impacts of climate change even in the very best models available. A notable 9% of total impacts estimated in the base FUND model are health related, and yet this estimate can vary substantially in both absolute value and relative value to other impacts without any changes to the health impact functions themselves depending on assumptions made about equity weights or reductions in vulnerability from future income growth. Additionally, a number of health impacts are either not currently included in SC-CO_2 estimates or are based on outdated literature, masking what is likely to be a much larger health impact quantity and proportion within the total SC-CO_2. Generally, an improved recognition of knowledge gaps, economic research needs, and policy needs has the potential to help shape the design of research studies, help prioritize areas of study, and open up new dissemination pathways to maximize the broader impact of climate and health research. This will require coordinated involvement between disciplines, which not only benefits economic researchers in formulating improved economic models of climate change but also may assist health researchers as they study climate-related health impacts. It is only by working together that economic and health researchers can best assist in providing policy relevant information that will be needed in the development and promulgation of effective climate policies. Professional medical and research societies are well positioned to serve as conveners of these needed interdisciplinary collaborations and are encouraged to take an active leadership role in facilitating updates to how health impacts are included in economic models of climate change.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data for this study from the FUND model are publicly available using Julia and the Mimi package. The FUND model itself, v3.12.1, can be found at: https://doi.org/10.5281/zenodo.4728124. The code for the specific analysis in this study can be found at: https://doi.org/10.5281/zenodo.4737985.

Acknowledgments
This work partially was supported by the National Science Foundation through the Network for Sustainable Climate Risk Management (SCRiM) under NSF cooperative agreement GEO-1240507. It was also supported in part by the Marron Institute of Urban Management at New York University.

References

Adler, M. D. (2016). Benefit-cost analysis and distributional weights: An overview. *Review of Environmental Economics and Policy*, *10*(2), 264–285. https://doi.org/10.1093/reep/rew005

Albertine, J., Manning, W., DaCosta, M., Stinson, K., Muilenberg, M., & Rogers, C. (2014). Projected carbon dioxide to increase grass pollen and allergen exposure despite higher ozone levels. *PloS One*, *9*(11). https://doi.org/10.1371/journal.pone.0111712

Anthoff, D., & Tol, R. S. J. (2009). The impact of climate change on the balanced growth equivalent: An application of FUND. *Environmental and Resource Economics*, *43*(3), 351–367. https://doi.org/10.1007/s10640-009-9269-5

Anthoff, D., & Tol, R. S. J. (2013). The uncertainty about the social cost of carbon: A decomposition analysis using FUND. *Climatic Change*, *117*(3), 515–530. https://doi.org/10.1007/s10584-013-0706-7

Anthoff, D., & Tol, R. S. J. (2018). *FUND: Climate framework for uncertainty, negotiation and distribution V3.10.0*. Zenodo.

Arbuthnott, K., Hajat, S., Heaviside, C., & Vardoulakis, S. (2016). Changes in population susceptibility to heat and cold over time: Assessing adaptation to climate change. *Environmental Health*, *15*, 33. https://doi.org/10.1186/s12940-016-0102-7

Balbus, J., Crimmins, A. R., Gamble, J. L., Easterling, D. R., Kunkel, K. E., Saha, S., & Sarofim, M. C. (2016). Ch. 1: Introduction: Climate change and human health. *The impacts of climate change on human health in the United States: A scientific assessment* (pp. 25–42). Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/J0VX0DFW

Barbero, R., Abatzoglou, J. T., Larkin, S., Kolden, C. A., & Stocks, B. (2015). Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*, *24*, 892–899. https://doi.org/10.1071/WF15083

Beach, R. H., Sulser, T. B., Crimmins, A., Cenacchi, N., Cole, J., Fukagawa, N. K., et al. (2019). Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: A modelling study. *Lancet Planet Health*, *3*(7), e307–e317. https://doi.org/10.1016/S2542-5196(19)30094-4

Bei, B., Bryant, C., Gilson, K. M., Koh, J., Gibson, P., Komiti, A., et al. (2013). A prospective study of the impact of floods on the mental and physical health of older adults. *Aging & Mental Health*, *17*(8), 992–1002. https://doi.org/10.1080/13607863.2013.799119

Bosello, F. (2014). Extension of the ICES CGE model with ecosystems. *CMCC research paper no 246*. https://doi.org/10.2139/ssrn.2603138

Bosello, F., Eboli, F., & Pierfederici, R. (2012). Assessing the economic impacts of climate change: An updated CGE point of view. In *FEEM working paper No 22012; CMCC research paper no 125*. https://doi.org/10.2139/ssrn.2004966

Bosello, F., & Parrado, R. (2014). Climate change impacts and market driven adaptation: The costs of inaction including market rigidities. *FEEM working paper no 0642014*. https://doi.org/10.2139/ssrn.2493015

Bosworth, R., Hunter, A., & Kibria, A. (2017). *Value of a statistical life: Economics and politics*. Strata Consulting.

Boxall, A. B. A., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P. D., et al. (2009). Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives*, *117*(4), 508–514. https://doi.org/10.1289/ehp.0800084

Calel, R., & Stainforth, D. A. (2017). *On the physics of three integrated assessment models* (pp. 1199–1216). American Meteorological Society. https://doi.org/10.1175/BAMS-D-16-0034.1

Carleton, T., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., et al. (2018). Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *Working paper no 2018-51*. https://doi.org/10.3386/w27599

Carleton, T. A., Jina, A., Delgado, M. T., Greenstone, M., Houser, T., Hsiang, S. M., et al. (2020). Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *Working paper no 27599*. https://doi.org/10.3386/w27599

Chang, A. Y., Robinson, L., Hammit, J. K., & Resch, S. C. (2017). Economics in 'global health 2035': A sensitivity analysis of the value of a life year estimates. *Journal of Global Health*, *7*(1), 010401. https://doi.org/10.7189/jogh.07.010401

Davis, J., Cox, W., Reff, A., & Dolwick, P. (2011). A comparison of CMAQ-based and observation-based statistical models relating ozone to meteorological parameters. *Atmospheric Environment*, *45*, 3481–3487. https://doi.org/10.1016/j.atmosenv.2010.12.060

Dodgen, D., Donato, D., Kelly, N., La Greca, A., Morganstein, J., Reser, J., et al. (2016). Ch. 8: Mental health and well-being. *The impacts of climate change on human health in the United States: A scientific assessment* (pp. 217–246). Washington, DC: U.S. Global Change Research Program.

Executive Order 13990. (2021). *Exec. order no. 13990, 86 fed. Reg. 7037*. Retrieved from https://www.govinfo.gov/content/pkg/FR-2021-01-25/pdf/2021-01765.pdf

Fankhauser, S., Tol, R. S. J., & Pearce, D. W. (1997). The aggregation of climate change damages: A welfare theoretic approach. *Environmental and Resource Economics*, *10*(3), 249–266. https://doi.org/10.1023/a:1026420425961

Fann, N. L., Nolte, C. G., Sarofim, M. C., Martinich, J., & Nassikas, N. J. (2021). Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, *4*(1), e2032064. https://doi.org/10.1001/jamanetworkopen.2020.32064

Gage, K. L., Burkot, T. R., Eisen, R. J., & Hayes, E. B. (2008). Climate and vector borne diseases. *American Journal of Preventive Medicine*, *35*(5), 436–450. https://doi.org/10.1016/j.amepre.2008.08.030

Gasparrini, A., Guo, Y., Sera, F., Vicedo-Cabrera, A. M., Huber, V., Tong, S., et al. (2017). Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planetary Health*, *1*(9), e360–e367. https://doi.org/10.1016/S2542-5196(17)30156-0

Hajat, S. (2017). Health effects of milder winters: A review of evidence from the United Kingdom. *Environmental Health*, *16*, 109. https://doi.org/10.1186/s12940-017-0323-4

Hanigan, I. C., Butler, C. D., Kokic, P. N., & Hutchinson, M. F. (2012). Suicide and drought in New South Wales, Australia, 1970-2007. *Proceedings of the National Academy of Sciences of the USA*, *109*(35), 13950–13955. https://doi.org/10.1073/pnas.1112965109

Honda, Y., Kondo, M., McGregor, G., Kim, H., Guo, Y.-L., Hijioka, Y., et al. (2014). Heat-related mortality risk model for climate change impact projection. *Environmental Health and Preventive Medicine*, *19*(1), 56–63. https://doi.org/10.1007/s12199-013-0354-6

Hope, C. (2013). Critical issues for the calculation of the social cost of CO_2: Why the estimates from PAGE09 are higher than those from PAGE2002. *Climatic Change*, *117*(3), 531–543. https://doi.org/10.1007/s10584-012-0633-z

Howard, P. (2014). *Omitted damages: What's missing from the social cost of carbon*. Retrieved from https://policyintegrity.org/publications/detail/omitted-damages-whats-missing-from-the-social-cost-of-carbon

Howard, P. (2019). The social cost of carbon: Capturing the costs of future climate impacts in US policy. In T. M. Letcher (Ed.), *Managing global warming* (pp. 659–694). Academic Press. https://doi.org/10.1016/b978-0-12-814104-5.00022-3

IWG. (2010). *Technical support document: Social cost of carbon for regulatory impact analysis under executive order 12866*. United States Government.

IWG. (2021). *Technical support document: Social cost of carbon, methane, and nitrous oxide interim estimates under executive order 13990*. United States Government.

Kessler, R. C., Galea, S., Gruber, M. J., Sampson, N. A., Ursano, R. J., & Wessely, S. (2008). Trends in mental illness and suicidality after Hurricane Katrina. *Molecular Psychiatry*, *13*(4), 374–384. https://doi.org/10.1038/sj.mp.4002119

Kolstad, E. W., & Johansson, K. A. (2011). Uncertainties associated with quantifying climate change impacts on human health: A case study for diarrhea. *Environmental Health Perspectives*, *119*(3), 299–305. https://doi.org/10.1289/ehp.1002060

Lake, I. R., Gillespie, I. A., Bentham, G., Nichols, G. L., Lane, C., Adak, G. K., et al. (2009). A re-evaluation of the impact of temperature and climate change on foodborne illness. *Epidemiology and Infection*, *137*(11), 1538–1547. https://doi.org/10.1017/s0950268809002477

Moore, F. C., Rising, J., Lollo, N., Springer, C., Vasquez, V., Dolginow, A., et al. (2018). Mimi-PAGE, an open-source implementation of the PAGE09 integrated assessment model. *Scientific Data*, *5*. https://doi.org/10.1038/sdata.2018.187

Munson, S. M., Belnap, J., & Okin, G. S. (2011). Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. *Proceedings of the National Academy of Sciences of the USA*, *108*(10), 3854–3859. https://doi.org/10.1073/pnas.1014947108

Murray, C. J. L., & Lopez, A. D., World Health Organization, World Bank, & Harvard School of Public Health. (1996). *The global burden of disease: A comprehensive assessment by mortality and disability from diseases, injuries, and risk factors in 1990 and projected to 2020*. Cambridge, MA: Harvard University Press.

NASEM. (2017). *Valuing climate damages: Updating estimation of the social cost of carbon dioxide*. https://doi.org/10.17226/24651

Nordhaus, W. (2008). *A question of balance: Weighing the options on global warming policies*. New Haven, CT: Yale University Press.

Nordhaus, W. (2014). Estimates of the social cost of carbon: Concepts and results from the DICE-2013R model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, *1*(1/2), 273–312. https://doi.org/10.1086/676035

Nordhaus, W. (2018). Evolution of modeling of the economics of global warming: Changes in the DICE model, 1992–2017. *Climatic Change*, *148*(4), 623–640. https://doi.org/10.1007/s10584-018-2218-y

Nordhaus, W., & Sztorc, P. (2013). *DICE 2013R: Introduction and user's manual*. Retrieved from http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_100413r1.pdf

Portmann, R. W., Daniel, J. S., & Ravishankara, A. R. (2012). Stratospheric ozone depletion due to nitrous oxide: Influences of other gases. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *367*(1593), 1256–1264. https://doi.org/10.1098/rstb.2011.0377

Roson, R., & van der Mensbrugghe, D. (2012). Climate change and economic growth: Impacts and interactions. *International Journal of Sustainable Economy*, *4*(3), 270–285. https://doi.org/10.1504/ijse.2012.047933

Schwartz, J. D., Lee, M., Kinney, P. L., Yang, S., Mills, D., Sarofim, M. C., et al. (2015). Projections of temperature-attributable premature deaths in 209 U.S. cities using a cluster-based Poisson approach. *Environmental Health*, *14*(85). https://doi.org/10.1186/s12940-015-0071-2

Tong, D. Q., Wang, J. X. L., Gill, T. E., Lei, H., & Wang, B. (2017). Intensified dust storm activity and Valley fever infection in the southwestern United States. *Geophysical Research Letters*, *44*, 4304–4312. https://doi.org/10.1002/2017GL073524

Trtanj, J., Jantarasami, L., Brunkard, J., Collier, T., Jacobs, J., Lipp, E., et al. (2016). Ch. 6: Climate impacts on water-related illness. *The impacts of climate change on human health in the United States: A scientific assessment* (pp. 157–188). Washington, DC: U.S. Global Change Research Program.

US EPA. (2018). *Regulatory impact analysis for the proposed emission guidelines for greenhouse gas emissions from existing electric utility generating units; revisions to emission guideline implementing regulations; revisions to new source review program*. U.S. Environmental Protection Agency.

USGCRP. (2016). *The impacts of climate change on human health in the United States: A scientific assessment*. Washington, DC: U.S. Global Change Research Program.

Van Dingenen, R., Crippa, M., Janssens-Maenhout, G., Guizzardi, D., & Dentener, F. (2018). Global trends of methane emissions and their impacts on ozone concentrations. *JRC science for policy report (EUR 29394 EN)*. Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/820175

Viscusi, K. W., & Masterman, C. J. (2017). Income elasticities and global values of a statistical life. *Journal of Benefit-Cost Analysis*, *8*(2), 226–250. https://doi.org/10.1017/bca.2017.12

Waldhoff, S., Anthoff, D., Rose, S., & Tol, R. (2011). The marginal damage costs of different greenhouse gases: An application of FUND. *Economics*, *8*, 1–33. https://doi.org/10.5018/economics-ejournal.ja.2014-31

Watts, N., Amann, M., Ayeb-Karlsson, S., Belesova, K., Bouley, T., Boykoff, M., et al. (2018). The Lancet Countdown on health and climate change: From 25 years of inaction to a global transformation for public health. *The Lancet*, *391*(10120), 581–630. https://doi.org/10.1016/S0140-6736(17)32464-9

WHO. (2018). *Climate change and health*. World Health Organization.